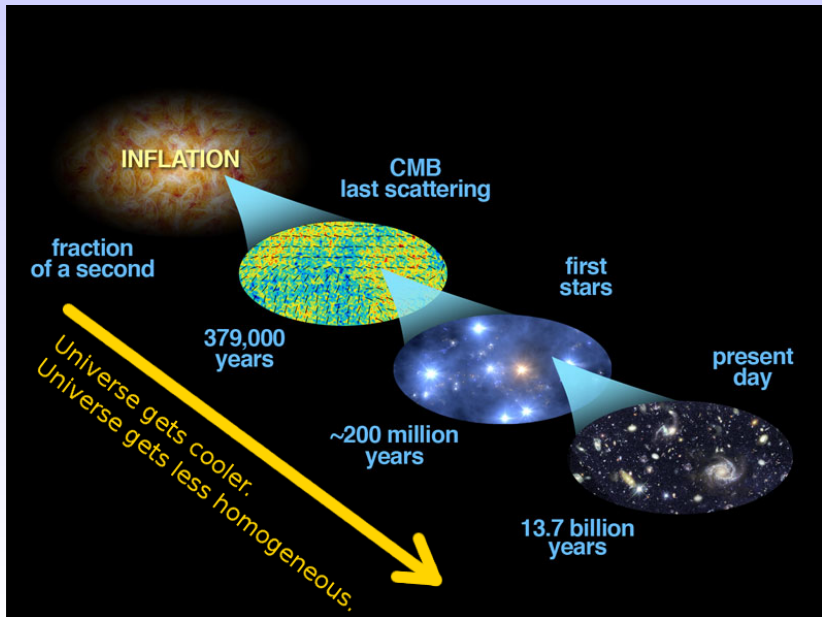


*Lyman- $\alpha$  forest in three  
dimensions:  
Measuring the Baryonic  
Acoustic Oscillations*

Anže Slosar, BNL

Physics Department Colloquium, 3/19/13

# *Universe's timeline*



# Cosmic pizza



Smallest component of Universe:

- ▶ *Baryons*: Stuff we see that makes up the world around us: electrons, protons, neutrons, ...
- ▶ Stuff we know & love

However, we also have:

- ▶ *Dark Matter*:
  - ▶ Cold, pressureless, non-interacting stuff
  - ▶ Collapses under its own gravity
  - ▶ Without it, Universe wouldn't have time to form galaxies, stars, planets and us
- ▶ *Dark Energy*:
  - ▶ Drives accelerated expansion of the Universe - biggest surprise of the last decade

# *The Dark Sector*

- ▶ *Macroscopic* behaviour well understood: we have many independent detections/confirmations of both dark components
- ▶ *Microscopic* understanding lacking:
  - ▶ How the dark sector fits with the standard model of particle physics?
  - ▶ Does gravity obey general relativity on all scales and at all energies?
  - ▶ How did it all begin? Is inflation an accurate description of the early universe?
- ▶ Dark Matter can be one of many postulated stable, weakly interacting particles – LHC might help solve the puzzle
- ▶ Dark Energy much more mysterious. It behaves like energy density of a vacuum, but its energy scale does not relate to anything we know.

# Measuring the expansion history of the Universe

- ▶ Many of these questions can be answered by measuring the expansion history of the Universe.
- ▶ One wants to measure *distance* or *Hubble parameter* as a function of *redshift*.
- ▶ How does this work?

# Redshift

- ▶ We often talk of redshift as a measure of “distance” in the Universe:

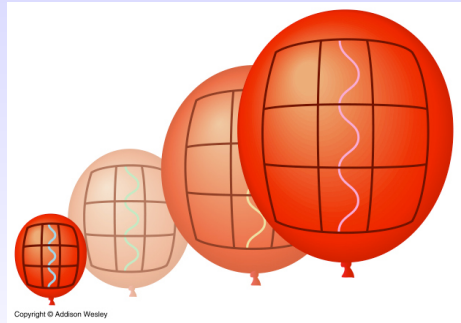
$$1 + z = \frac{\lambda_o}{\lambda_e}$$

- ▶ It obviously doesn't have the right units to be a “distance”
- ▶ Redshift is really a measure of how much the Universe has expanded since light was emitted:

$$a(z) = \frac{1}{1 + z}$$

- ▶ As the Universe expands, the wavelength of propagating light expands together with it.
- ▶ Hubble parameter measures the logarithmic expansion rate:

$$H(a) = \frac{\text{velocity}}{\text{distance}} = \frac{d_{\text{comoving}} \dot{a}}{d_{\text{comoving}} a} = \frac{\dot{a}}{a}$$



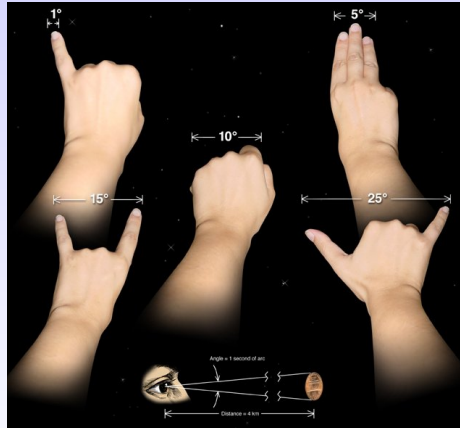
# Distance

- ▶ One deals with Friedman-Robertson-Walker metric:

$$ds^2 = dt^2 - a(t)^2(dr^2 + S(r)^2 d\Omega^2)$$

- ▶ There is no clear definition of distance, but one can *define* distances operationally
- ▶ Luminosity distance is distance inferred by looking at the brightness of an object of known luminosity
- ▶ Angular diameter distance is distance by looking at the angular size of an object of known size.
- ▶ All distance are related to light travel, for which  $ds^2 = d\Omega^2 = 0$ , so

$$r = \int \frac{dt}{a} = \int \frac{dt}{ada} = \int \frac{a}{\dot{a}} dz = \int \frac{dz}{H(z)}$$



## *So far geometry, now dynamics*

- ▶ FRW metric is the most general space-time metric consistent with spatial homogeneity and isotropy:

$$ds^2 = dt^2 - a(t)^2(dr^2 + S(r)^2 d\Omega^2)$$

- ▶ Add Einstein field equations

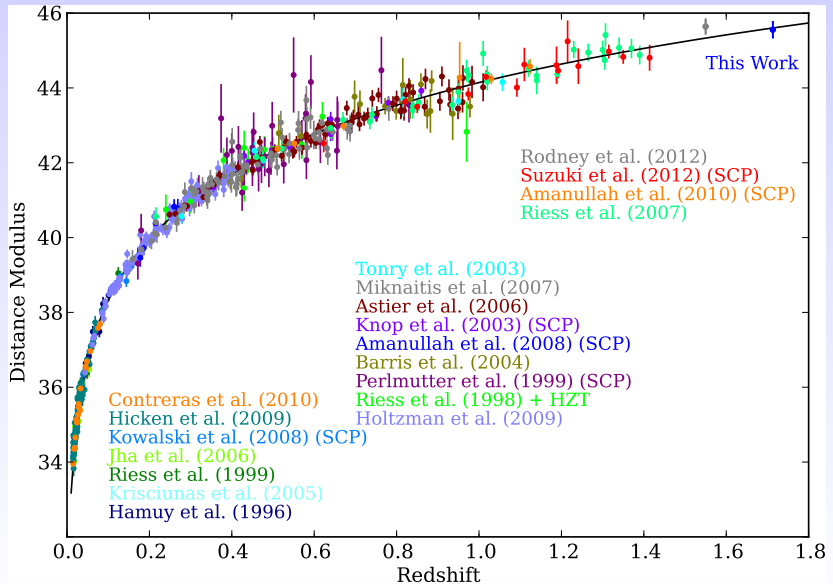
$$G_{\mu\nu} + g_{\mu\nu}\Lambda = 8\pi T_{\mu\nu}$$

- ▶ and get the Friedman equation:

$$H^2(a) = \frac{\dot{a}^2}{a^2} = H_0 \sqrt{\Omega_r a^{-4} + \Omega_m a^{-3} + \Omega_k a^{-2} + \Omega_\lambda(z)} \quad (1)$$

- ▶ So, measuring either  $H(z)$  as a function of  $z$  or measuring distances  $D(\int H^{-1}(z)dz)$  one can learn about make up of the universe and its constituents

# Hubble diagram from Supernovae

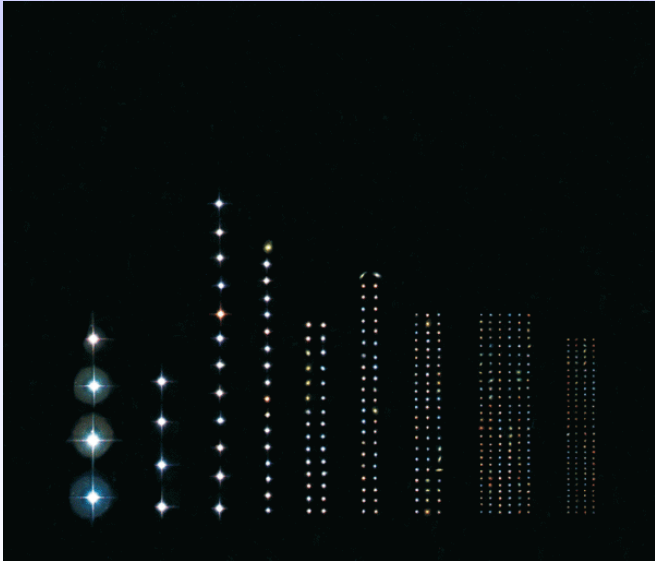


# *Judging distances*



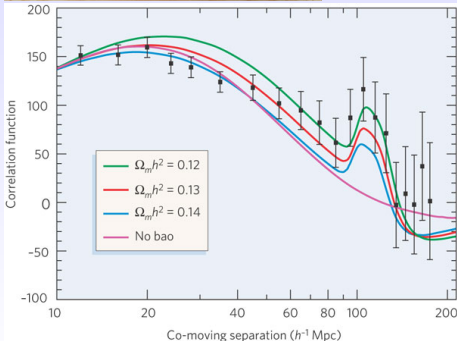
I see stuff.

# *Judging distances*



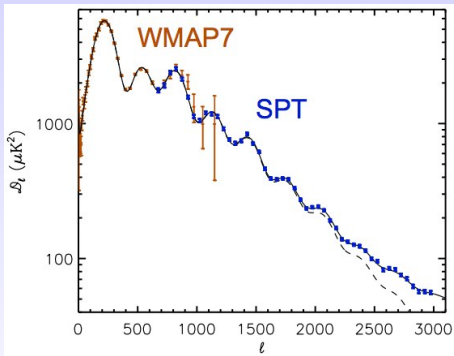
(Ordering by Urs Wehrli.)

# What is BAO?

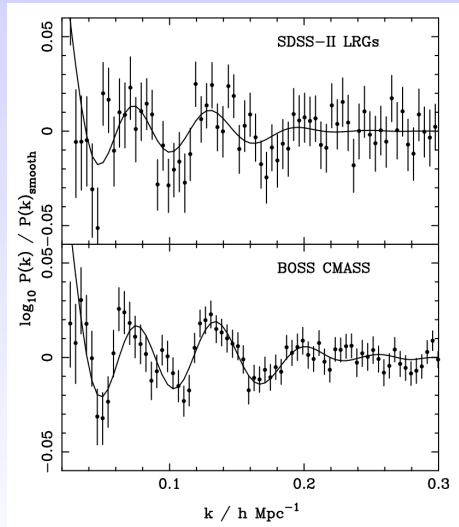


- ▶ Before recombination (i.e. formation of hydrogen atoms), primordial plasma supports acoustic waves
- ▶ Sound waves travel through Universe as long as it is in primordial plasma state
- ▶ The characteristic scale is imprinted as a small bump into the correlation properties of dark matter
- ▶ It acts as a standard ruler, allowing very robust measurements of the expansion history of the universe.

# What is BAO?

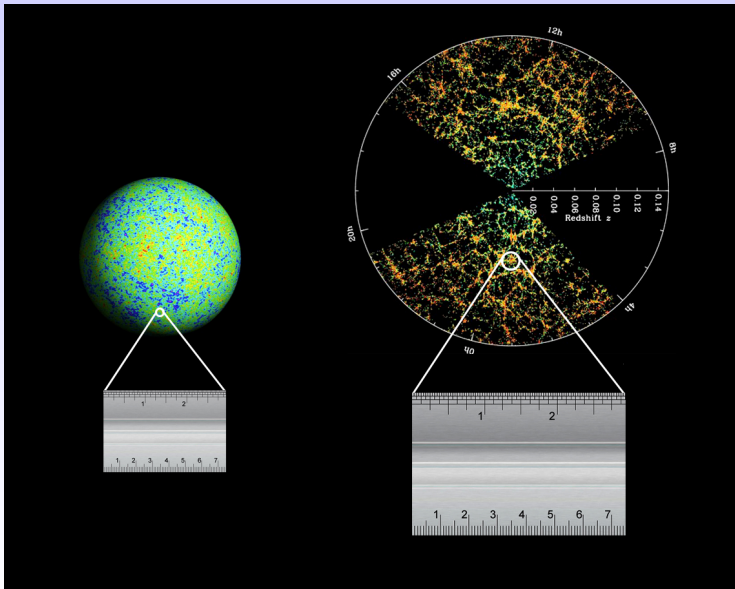


BAO in Cosmic Microwave Background

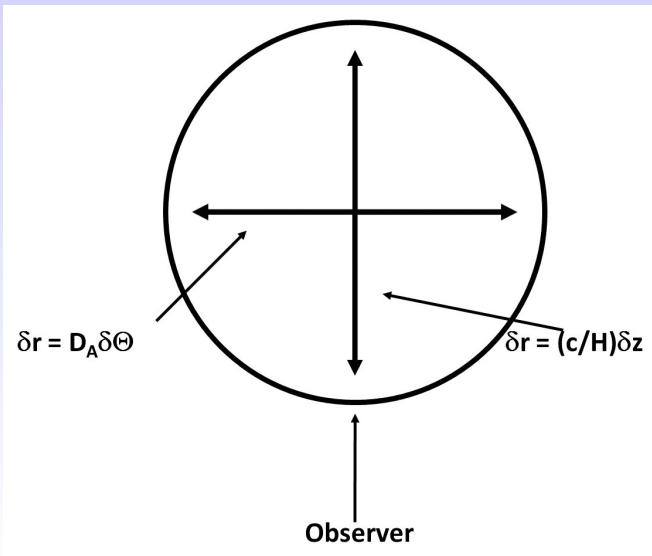


BAO in CMASS galaxies

# *BAO is a static ruler*



*BAO is a static ruler*



# Measuring Density fields

- ▶ Careful might have noticed a leap from dark matter density fluctuations to galaxies
- ▶ There are very strong arguments based on locality. Assuming the galaxy-formation process is a **stochastic and arbitrarily complicated, but local** process

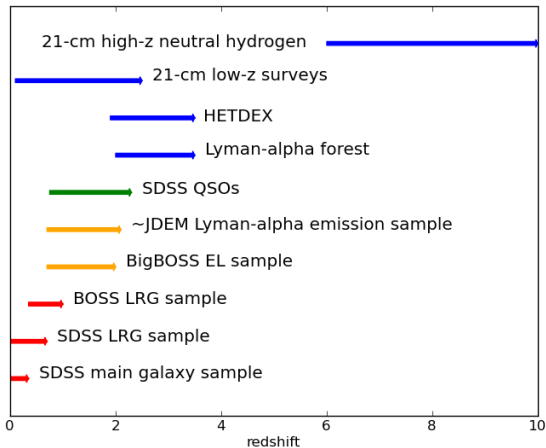
$$\delta_g(\mathbf{r}) = F(\delta_{\text{dm}}(\mathbf{r})), \quad (2)$$

then on large<sup>\*</sup> scales

$$P_g(k) = b^2 P_{\text{dm}}(k) + \text{const.} \quad (3)$$

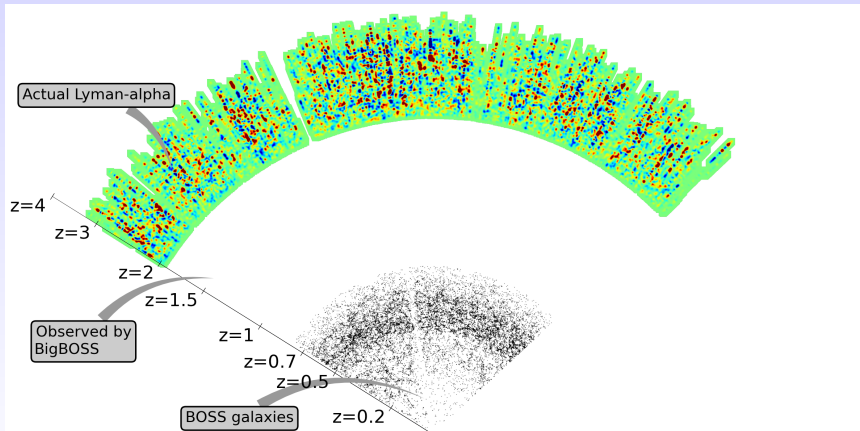
- ▶ This is true for any local process.
- ▶ <sup>\*</sup> larger than locality scales and such that  $\delta_g(k) \ll 1$ ,  $\delta_{\text{dm}}(k) \ll 1$

# Measuring Density fields

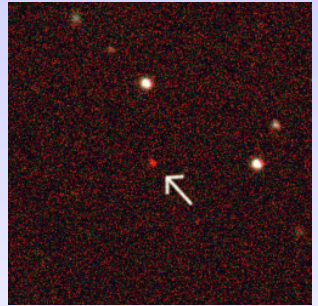
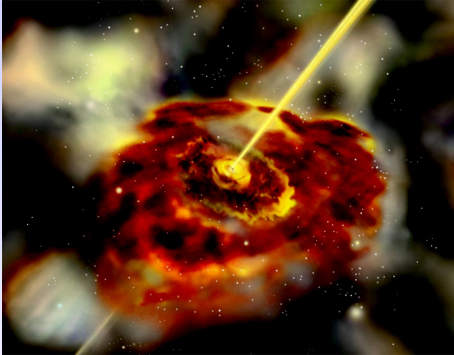


- ▶ To measure BAO, one needs a tracer of dark matter
- ▶ Lyman- $\alpha$  forest pretty unique in probing redshift 2-3 universe
- ▶ Volume probed is very, very large
- ▶ Systematics very different to galaxy surveys
- ▶ At  $z < 2$  limited by forest moving into UV
- ▶ At  $z > 3.5$  limited by faintness and number-density of quasars

# Measuring Density fields

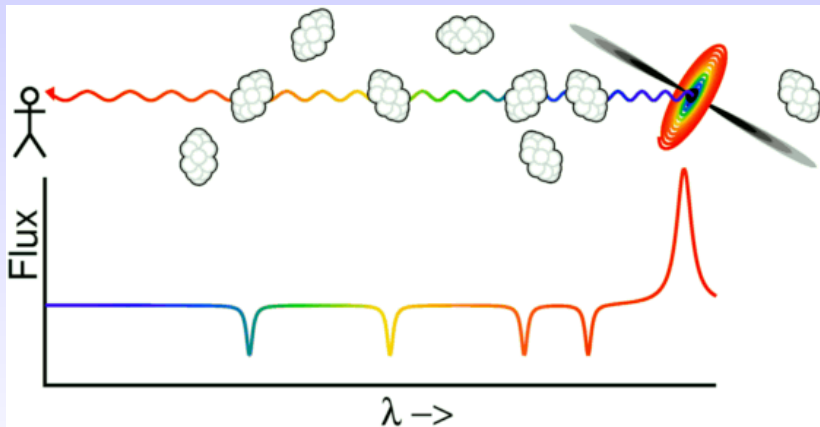


# *What are quasars*



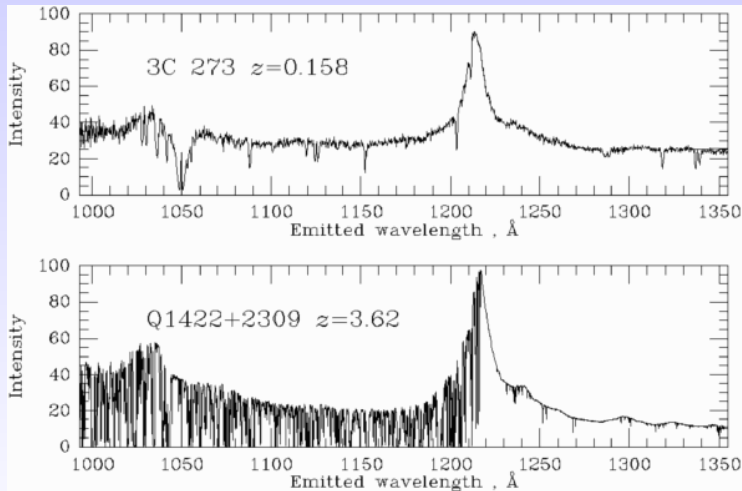
- ▶ Brightest things in the Universe
- ▶ Powered by energetic active galactic nuclei – can see them very far
- ▶ Featureless spectrum with a few broad emissions
- ▶ Understanding of underlying physics not important for our application.

# *Lyman- $\alpha$ forest*



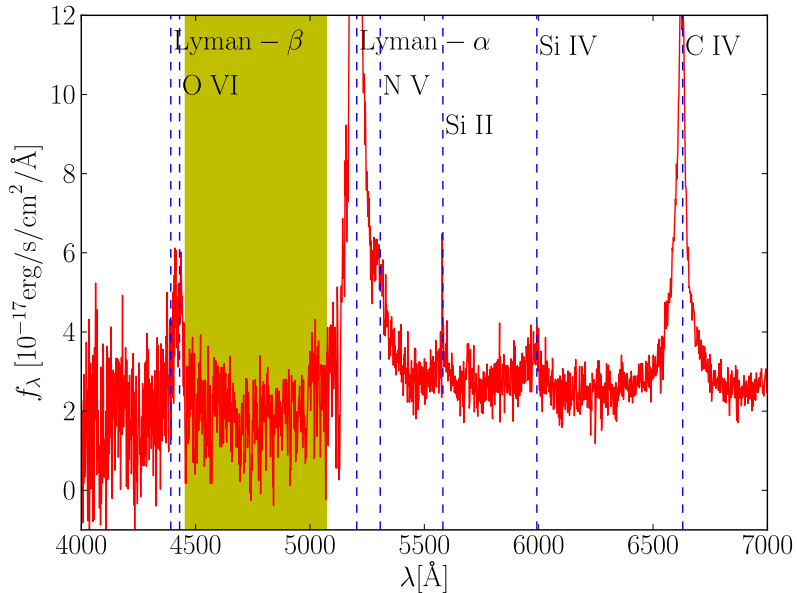
Neutral hydrogen absorbs light from distant quasars blue-ward of Lyman- $\alpha$  emission.

# Lyman- $\alpha$ forest

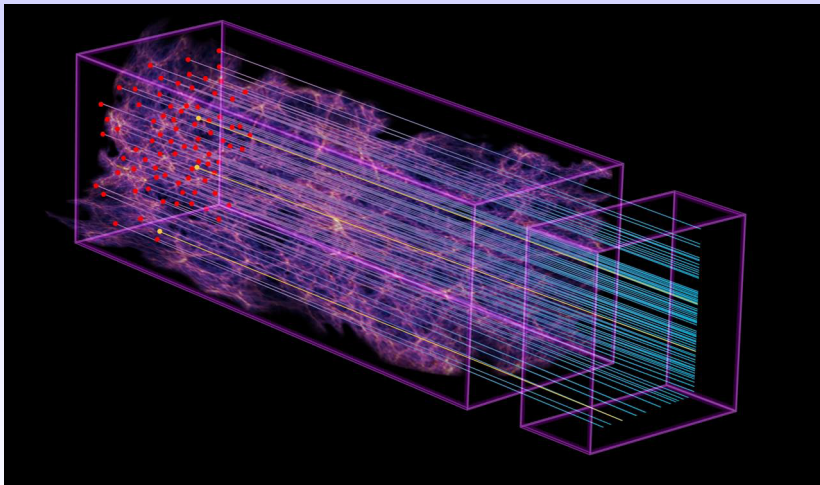


Neutral hydrogen absorbs light from distant quasars blue-ward of Lyman- $\alpha$  emission.

# *BOSS spectra*



# *3D sampling of the universe*



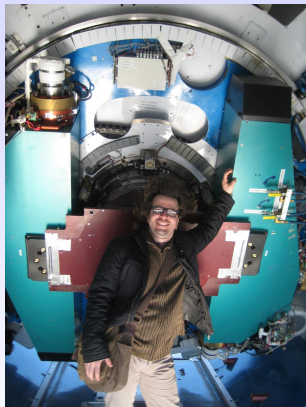
# *Baryon Oscillation Spectroscopic Survey (BOSS)*

- ▶ BOSS is one of 4 experiments making up SDSS3.
- ▶ Uses 2.5m SDSS telescope
- ▶ Large etendue
- ▶ A 1000 fiber spectrograph
- ▶ Medium resolution:  $R \sim 2000$
- ▶ Wavelength: 360nm (UV) 1000 nm (IR)

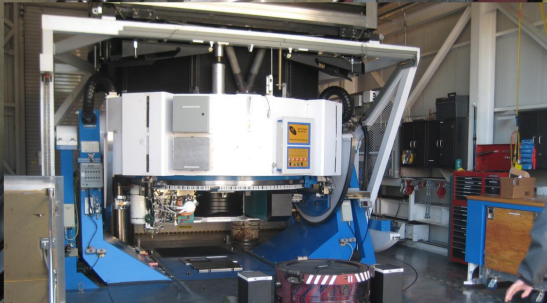
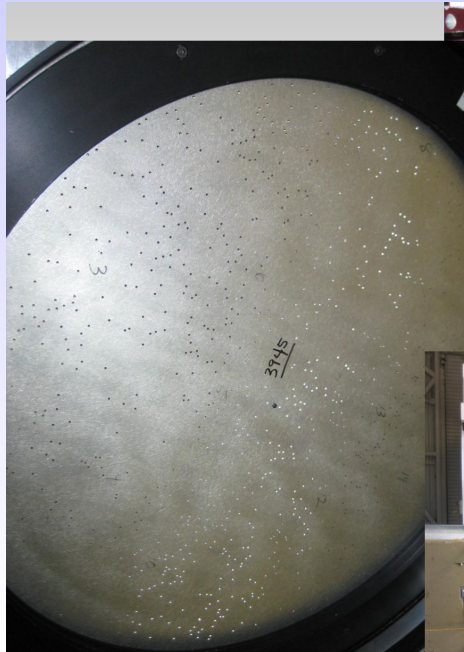


# *Baryon Oscillation Spectroscopic Survey (BOSS)*

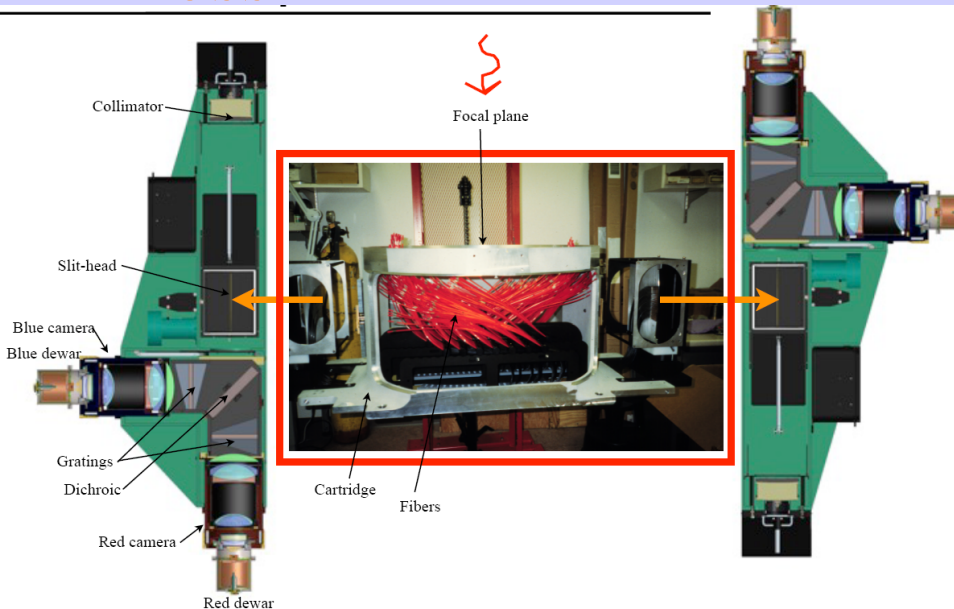
- ▶ Will get spectra of
  - ▶ 1 million LRG ( $z < 0.7$ )
  - ▶ 160,000 QSOs with usable forest
- ▶ Survey over half done, over 100,000 high- $z$  QSOs in hand.
- ▶ Primary science goal is to measure dark energy through Baryonic Acoustic Oscillations.



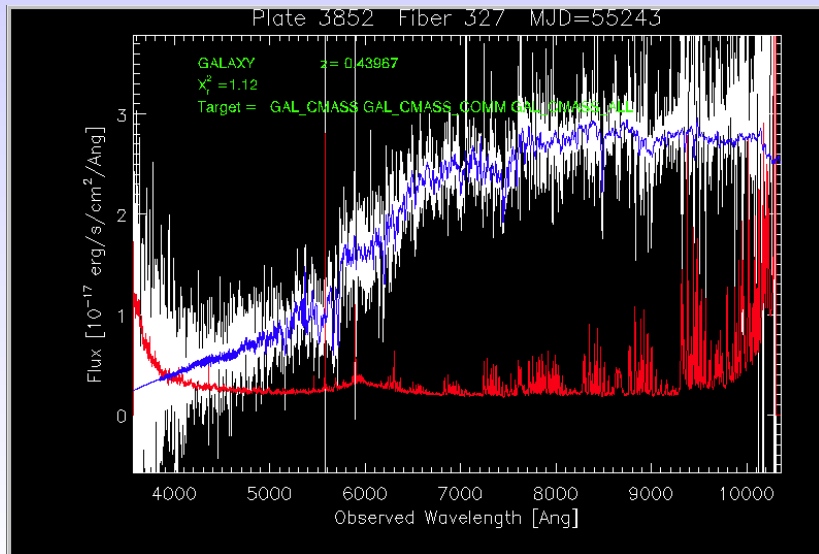
# *How BOSS works?*



# How BOSS works?

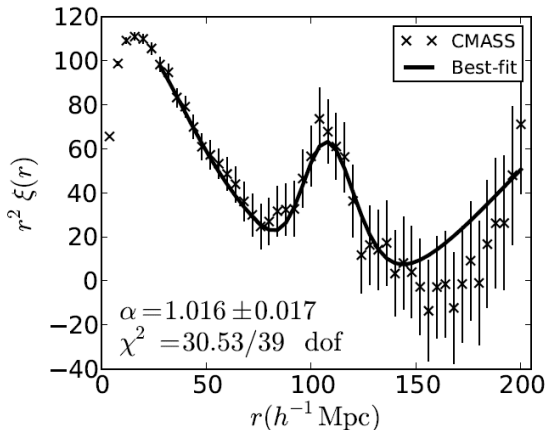


# *BOSS spectra*



# BAO measurements with galaxies

- ▶ Measuring BAO at low redshift ( $z < 1.0$ ) became a standard lore of cosmology.
- ▶ You can have broadband contaminants that don't affect your measurement

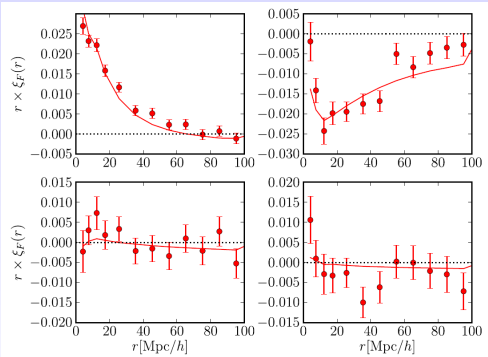


# *History of BOSS Lyman- $\alpha$*

- ▶ Traditionally, Lyman- $\alpha$  forest has been used on a quasar by quasar basis: measuring 1D power spectra
- ▶ Nobody has done 3D Lyman- $\alpha$  to cosmological scales before BOSS
- ▶ We published first proof-of-concept paper in 2011
- ▶ Two papers with Lyman- $\alpha$  forest BAO appearte recently:
  - ▶ Busca et al paper: [arXiv:1211.2616](#)
  - ▶ Slosar et al apper: [arXiv:1301.3459](#)



# The 2011 analysis: $\xi$ push

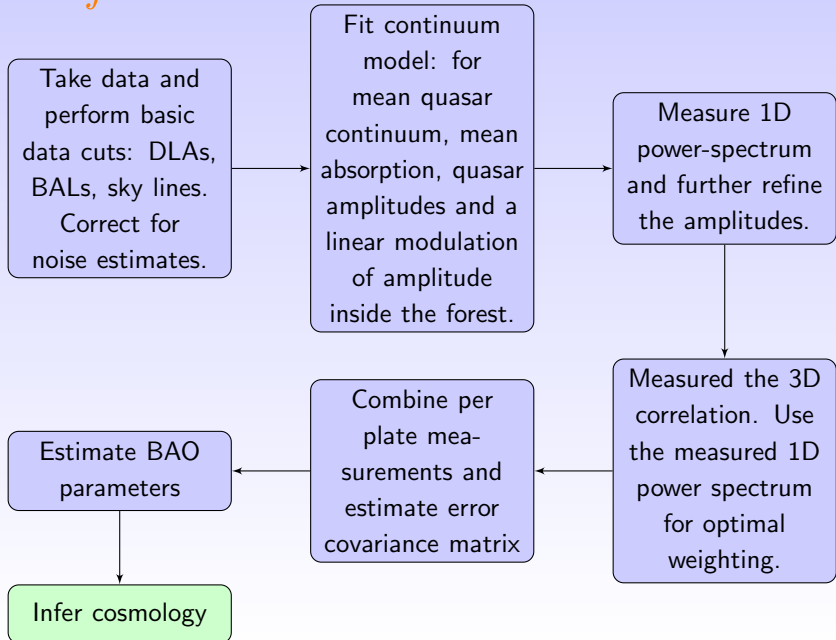


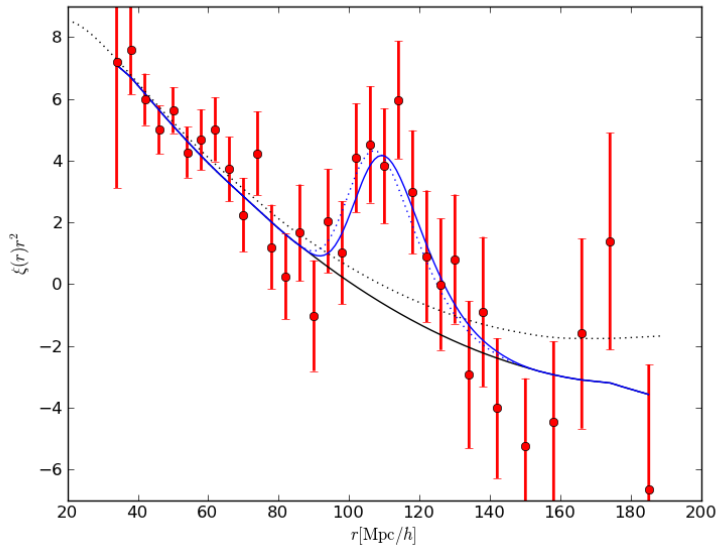
- ▶ Clear detection of correlations with no significant contamination
- ▶ The measured correlation function is distorted due to continuum fitting
- ▶ Analysis is harder than galaxy analysis:
  - ▶ Redshift-space distortions always matter
  - ▶ Redshift-evolution does matter

# *Data Sample*

- ▶ We all used DR9 based Value Added Catalog
- ▶ Quasars visually inspected
- ▶ DLAs, BAL identified
- ▶ 60,639 QSOs in  $2.1 < z < 3.5$
- ▶ 58,229 quasars after cuts
- ▶ 15 sets of full-dataset synthetic data

# Data flow





# *Fitting bump*

We did a very careful job fitting the BAO position. There is an app for it: [arXiv:1301.3456](#).

There were a couple of lessons learned:

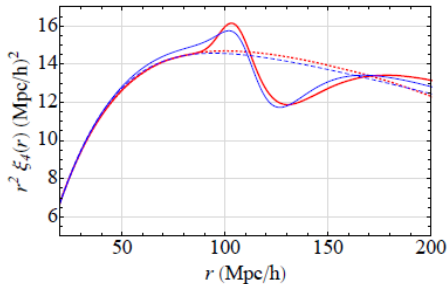
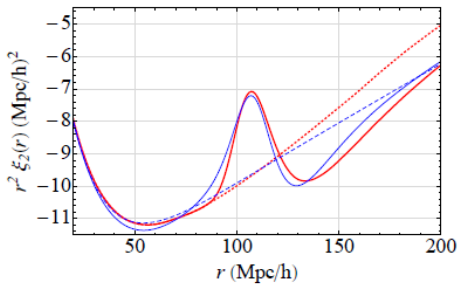
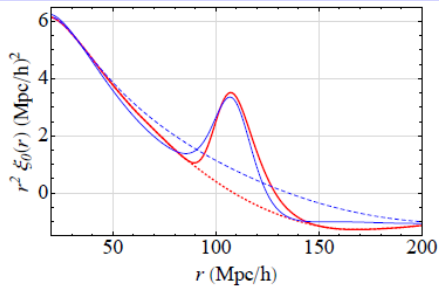
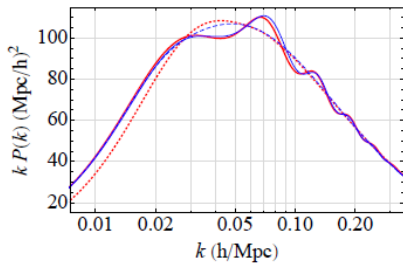
- ▶ There is no clean way to de-couple peak from the rest
- ▶ There is no clean way to measure information just from the BAO

Our basic model for the data is:

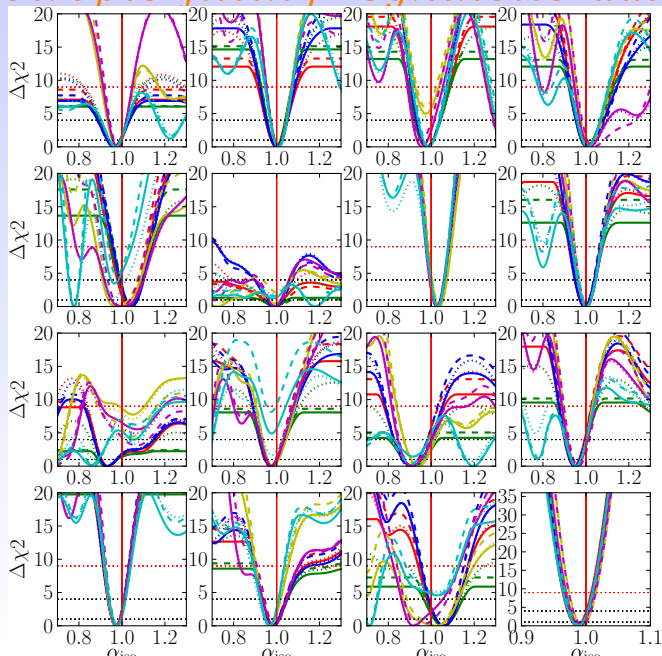
$$\xi_{\text{observed}}(\Delta \log \lambda, s, z) = \xi_{\text{cosmo}}(r_{\parallel}, r_{\perp}, \alpha_{\parallel}, \alpha_{\perp})(1 + B_m(r, \mu, z)) \\ + B_a(r, \mu, z)$$

Occasionally we also use  $\alpha_{\text{iso}} = \alpha_{\perp} = \alpha_{\parallel}$ .

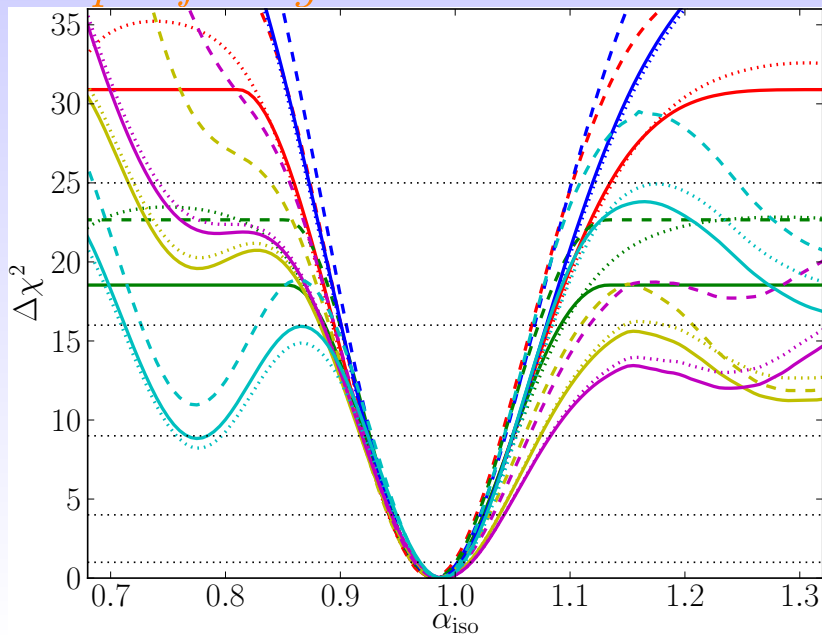
# Bumps



# Isotropic fitting: synthetic data

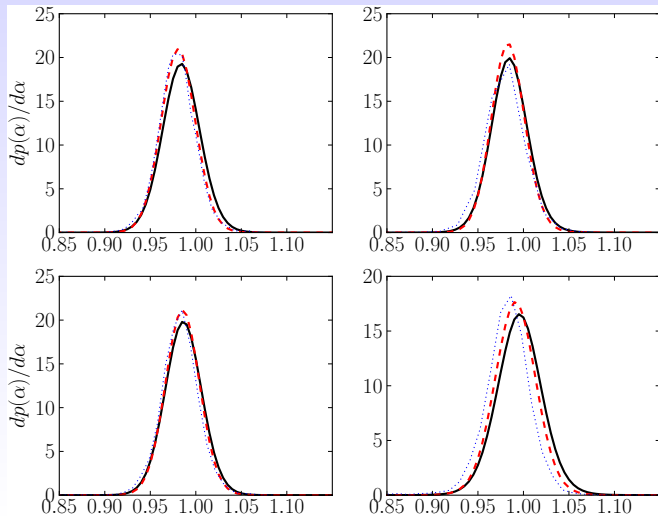


## *Isotropic fitting: real data*

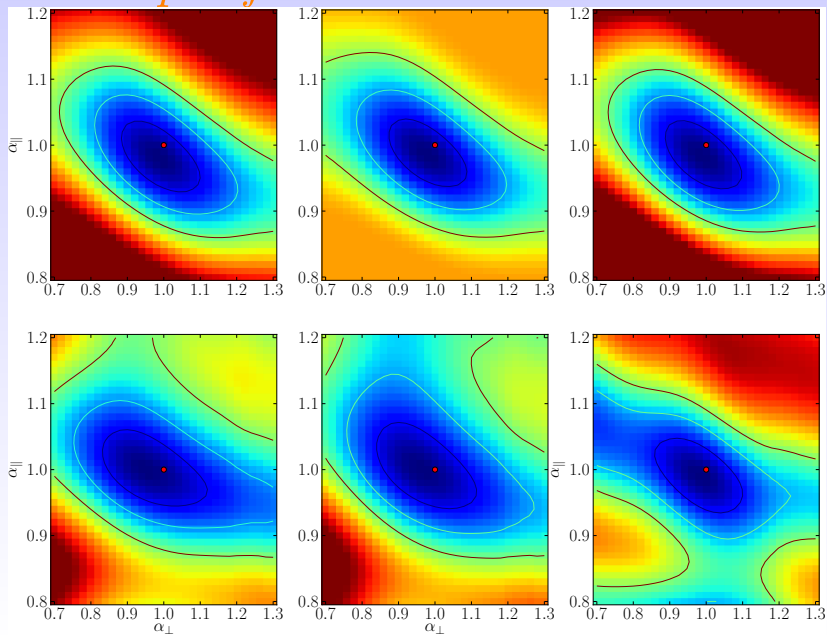


# Comparing with bootstrap

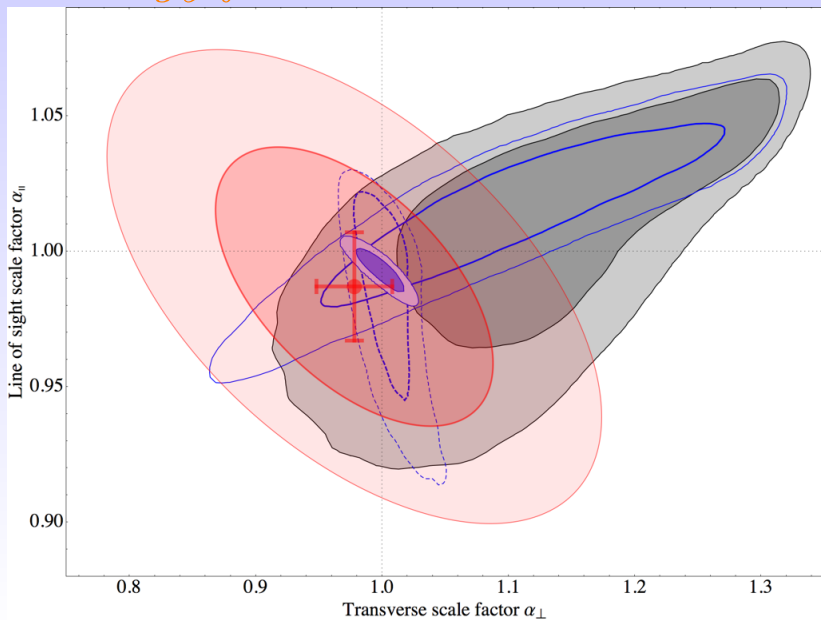
- ▶ Bootstrap does seem to match the M3 matrix...
- ▶ Note that we are really comparing apples and smurfs here: what is the effective prior of the bootstrap analysis?



# Anisotropic fit with data



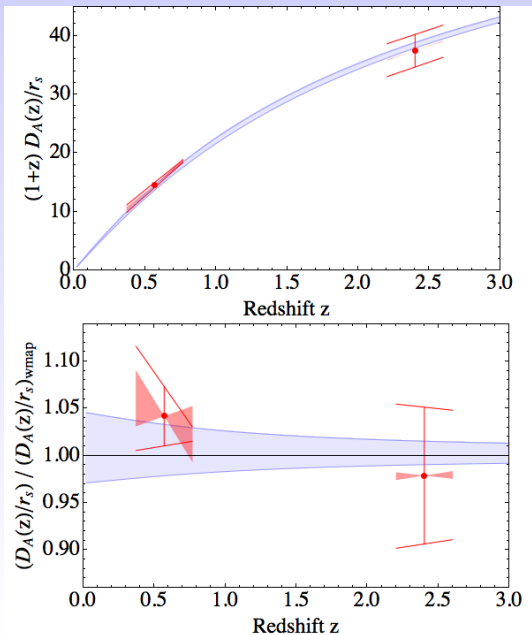
# Cosmology fits



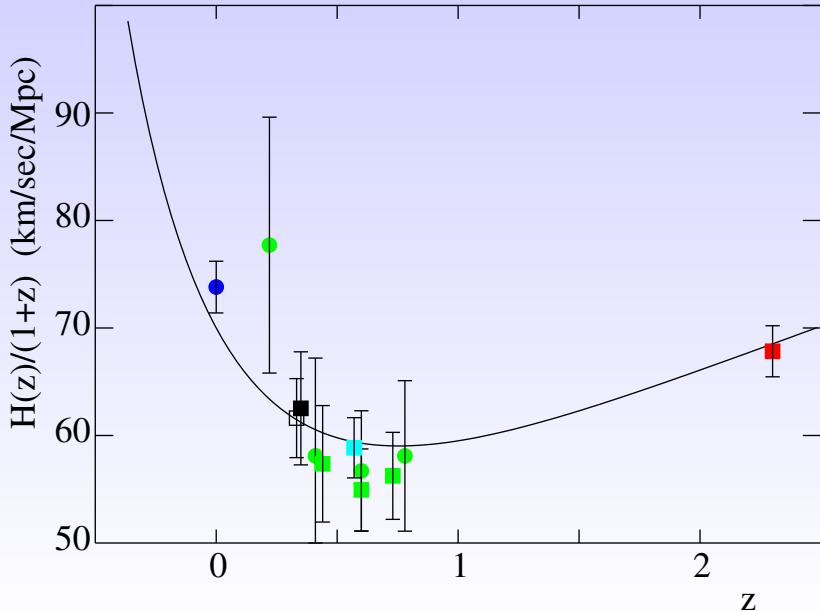
# Distance plot

A cunning plot:

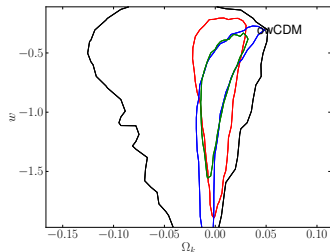
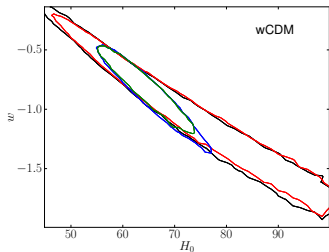
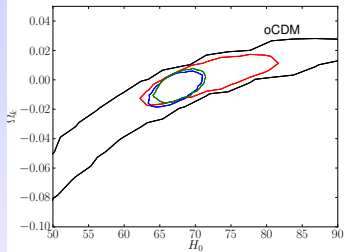
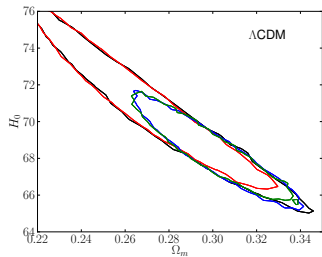
- ▶ Error-bars are distance errors
- ▶ bow-ties are Hubble-parameter measurements at central value: i.e. slopes
- ▶ Slanting of upper and lower errorbar is the correlations between parallel and perpendicular direction measurement.



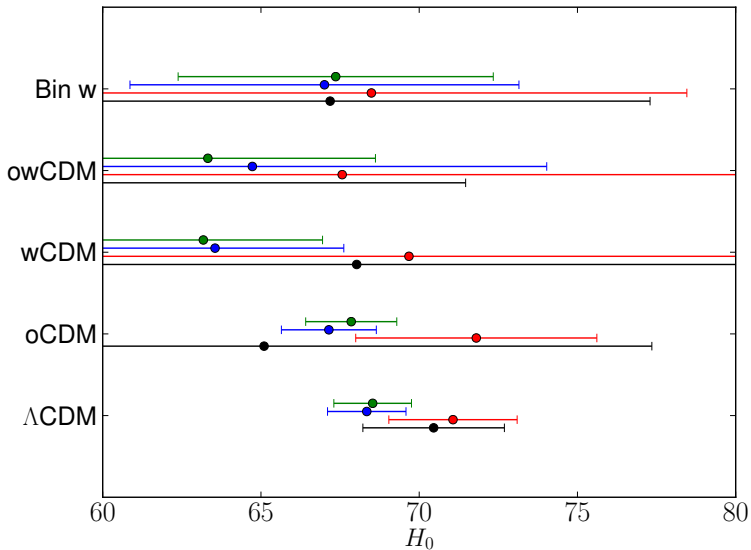
# *Hubble's parameter plot*



# Cosmology fits



# Cosmology fits



# Conclusions

- ▶ We measure the BAO in the Lyman- $\alpha$  forest.
- ▶ The significance is  $3 - 5\sigma$
- ▶ consistent with  $\Lambda$ CDM,  
 $100 \times (\alpha_{\text{iso}} - 1) =$   
 $-1.6^{+2.0}_{-2.0} \quad +4.3_{-4.1} \quad +7.4_{-6.8} \text{ (stat.) } \pm 1.0 \text{ (syst.)}$
- ▶ Many other projects going on with Lyman- $\alpha$  forest in BOSS: cross-correlations, 1D power spectra, Lyman- $\beta$  forest, ...
- ▶ Very much remains to be done....

